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LABORATORY TESTING ON COMPACTED, PARTIALLY SATURATED SILTY AND SANDY SOILS

Abstract. This Technical note summarizes some experimental results concerning the effective strength parameters (c' — φ') and the saturated coefficient of hydraulic conductivity (k) of silty and sandy soil specimens that have been compacted at different compaction degrees. The tested soils were used for the construction/refurbishment of existing levees. The effective strength parameters were obtained from conventional triaxial loading compression tests. Specimens were compacted at different percentages of the maximum (optimum) dry density and at the optimum water content. The maximum dry density and optimum water content were determined according to the Modified Proctor method. Specimens with different percentages of the maximum dry density at the optimum water content were obtained in the Proctor mold by using different compaction energy. Levees (and more generally any type of earthworks) can increase their water content because of intense rainfall or repeated floods. Therefore, the strength parameters of fully saturated specimens have also been experimentally determined. The saturated coefficient of hydraulic conductivity has been inferred from variable head permeability measurements that were performed in specially equipped oedometers. This coefficient has been measured in the case of specimens compacted at different compaction degrees and at different initial water contents (i. e. saturation degrees). The effect of compaction degree on strength and permeability parameters has been shown. As for the strength parameters, the effect of partial saturation (suction) has also been shown.

Keywords: strength parameters, saturated coefficient of hydraulic conductivity, silty and sandy soil specimens, compaction degree, existing levees, triaxial loading compression tests, compaction energy.

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ЛАБОРАТОРНЫЕ ИСПЫТАНИЯ УПЛОТНЕННЫХ, ЧАСТИЧНО НАГРУЖЕННЫХ ИЛИСТЫХ И ПЕСЧАНЫХ ГРУНТОВ

Аннотация. В статье приведены результаты экспериментального определения параметров прочности и коэффициента гидравлической проводимости образцов илистых и песчаных грунтов при разных степенях уплотнения. Испытуемые грунты использовались для строительства (ремонта) существующих дамб. Параметры прочности получены на основе трехосных компрессионных испытаний. Образцы уплотняли при различных процентах максимальной (оптимальной) сухой плотности и при оптимальном содержании воды. Максимальная сухая плотность и оптимальное содержание воды определялись в соответствии с модифицированным методом Проктора. Образцы с разным процентом максимальной сухой плотности при оптимальном содержании воды были получены в пресс-форме Проктора при разных величинах энергии уплотнения. В дамбах количество воды может увеличиться вследствие интенсивных ливней или повторяющихся наводнений. Экспериментально определены параметры прочности полностью водонасыщенных образцов. Коэффициент гидравлической проводимости получен на основе измерения переменной проницаемости с помощью специально оборудованных одометров. Коэффициент был получен при разных степенях уплотнения грунтов и при различных степенях насыщения. Показано влияние степени уплотнения на параметры прочности и проницаемости, а также влияние частичной насыщенности (всасывания) на параметры прочности.

Ключевые слова: показатели прочности, коэффициент гидравлической проводимости, образцы илистых и песчаных свойств, степень уплотнения, существующие дамбы, трехосные компрессионные испытания, энергия сжатия.

Introduction

In common practice, at least in Italy, the construction of any type of earthwork is based on the prescription of a given construction material (generally referring to AASTHO M145, 1991 [1]) and of compaction method (equipment, number of passes, layer height). As for the control, it is usually prescribed to obtain at least a compaction degree of 90 % of the maximum dry density (modified Proctor method, ASTM D1557, 2012, [6]). Such an approach is essentially the same adopted for the construction of road embankments. On the Author experience, a compaction degree of 90 % is hardly obtained in case of soils containing fines, when using conventional compaction machines. Usually, in various field works, we observed compaction degrees in between 80 and 90 %.

On the other hand, the geotechnical design/assessment of earthworks should refer to the expected performance of given work. In particular, the design/assessment of both new and existing levees should require, at least, the knowledge of strength and permeability parameters of the construction materials in the compacted state.

Since the pioneering works [18–20] it is accepted that strength parameters of compacted and unsaturated soils are mainly controlled by the structure forming during the compaction process as well as suction (capillary effects). Many papers give information about strength of compacted unsaturated soils. These studies concern the effect of different mix (sand and clay) and types of soils and give information on the unconfined compression strength or (to a less extent) on the effective strength parameters. It is worth mentioning as examples the works [9, 10, 21].

90 % of the optimum was inferred. Block samples were not retrieved immediately after the levee construction. Therefore, the water content does not correspond to that during levee formation.

It is worth noting that TC soil was sieved in order to eliminate the fraction with a diameter greater than 2 mm. As for the 808I soil the fraction greater than 0.2 mm was eliminated. Laboratory testing and data reported in Table 1 refer to these materials. Only the tests on specimens from block samples refer to the original TC soil. In Fig. 1a the grain size distribution curves of the original soil and of the same soil after elimination of the coarser fraction (scalped) are shown.

Fig. 1b shows the compaction curves (Modified Proctor Method) of scalped 808I and TC soils as well as that of TC soil from block samples (not scalped).

In the following the term "compacted specimens" is used to identify those that have been compacted in the Proctor mold. "Undisturbed specimens" are those obtained from block samples.

Table 1

Soil classification. AGI (1997), AASHTO M 145 (1991), ASTM 2487 (2011), ASTM D1557 (2012)

Soil Name	LL (%)	LP (%)	IP (%)	AGI (1997)	USCS	AASHTO	Gs (–)	Modified Proctor (Scalped)	
								$\gamma_{d,\,opt}$ kN/m^3	w_{opt} (%)
TC	25.1	5.8	19.3	Clayey Silt with Sand (gravel < 10 %)	CL	A6	2.67	19.80	11.5
808I	–	–	–	Clayey Sand with Silt	SM	A4	2.74	18.86	11.5

Based on the most recent experimental evidences, the strength parameters as well as the saturated hydraulic conductivity mainly depend on the degree of compaction and the degree of saturation at the end of compaction (see as an example Tatsuoka [21]).

This paper is aimed at experimentally determining the effective strength parameters and saturated permeability of two different soils with different compaction degrees.

Tested Materials

Two different types of soils were used, TC and 808I. Soil classification is summarised in Table 1 [11, 12, 13, 16]. Fig. 1a shows the grain size distribution curves. The maximum dry density and optimum water content were determined according to the modified Proctor method). The maximum dry unit weight and optimum water content are also reported in Table 1. Atterberg limits were determined according to ASTM D4318 [7]. The TC soil was used to construct a levee few hundreds of m long and with a height ranging between 2 to 4 meters. From the crest of the bank two block samples were retrieved for control purposes. The grain size distribution curves of these two samples are also shown in Fig. 1a. From block samples a dry density in between 80 and

Oedometer Test Results and Experimental Determination of the Coefficient of Permeability

The permeability of the two soils was obtained from oedometer tests:

a) indirectly, by the estimate of Cv (according to the Taylor [22] method);

b) directly, by using the oedometer as a rigid wall permeameter.

More specifically, variable head permeability tests were carried out. The test setup is shown in Fig. 2. The standard oedometer — test equipment was ad — hoc modified. The hydraulic load was applied at the bottom of the oedometer cell through the lower porous filter. The water could flow only throw the soil sample thanks to o-rings located between the two metal rings and between the outer metal ring and the base of the oedometer cell. Samples were compacted in the Proctor mold according to the modified Proctor method (ASTM D1557–12 [6]). Different initial water contents led to different dry densities. After compaction, the samples were extracted from the Proctor mold and specimens were trimmed and transferred into the oedometer cell according to the usual procedures. Such operations caused a certain disturbance and the initial void ratio of the specimen

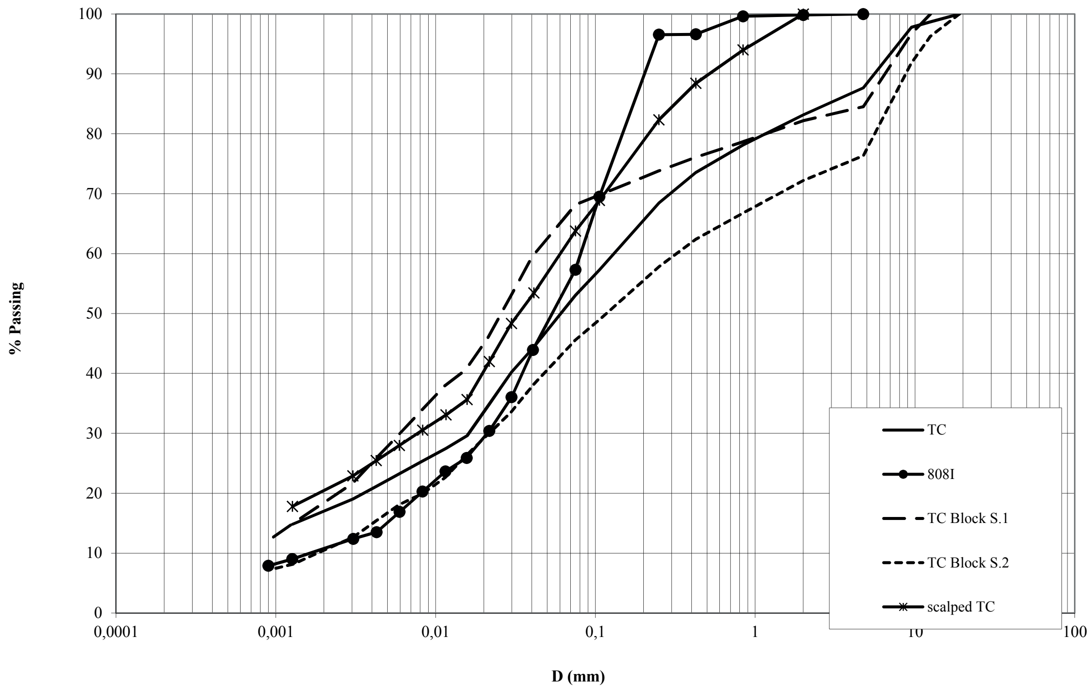

Fig. 1a. Grain size distribution curves

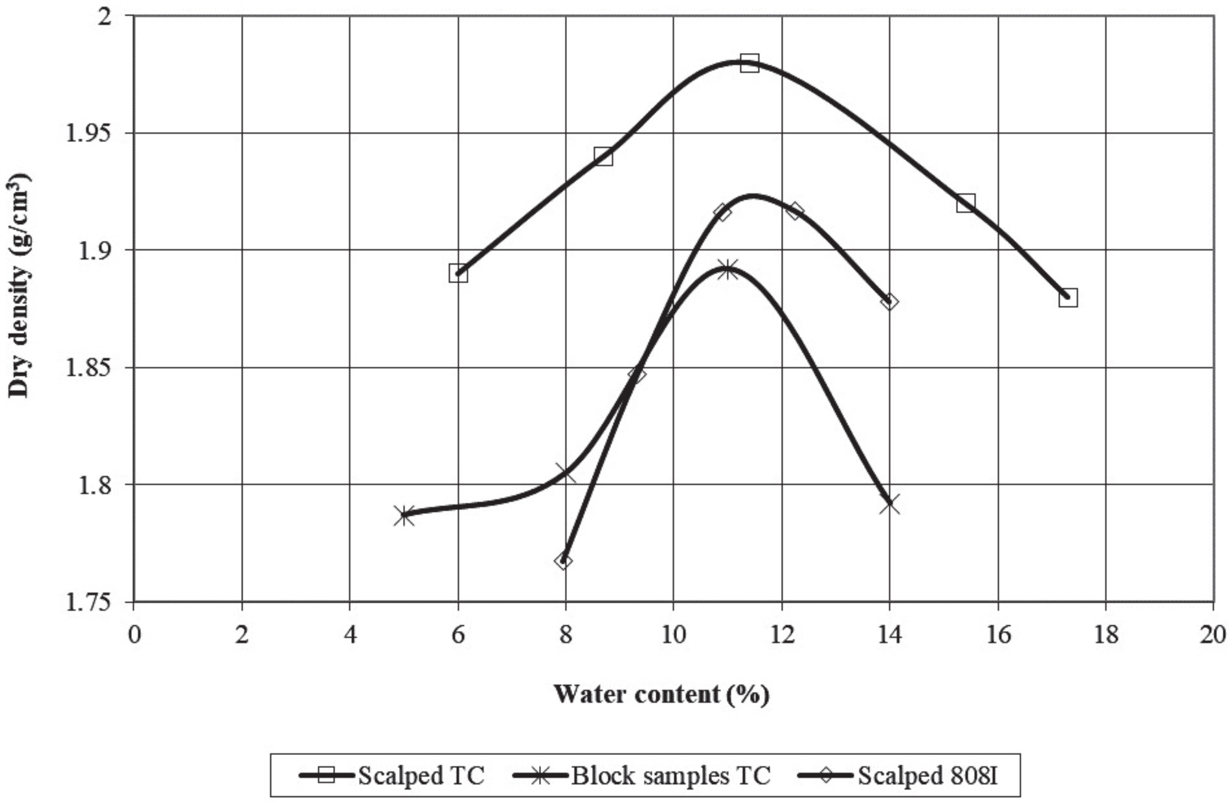

Fig. 1b. Compaction curves

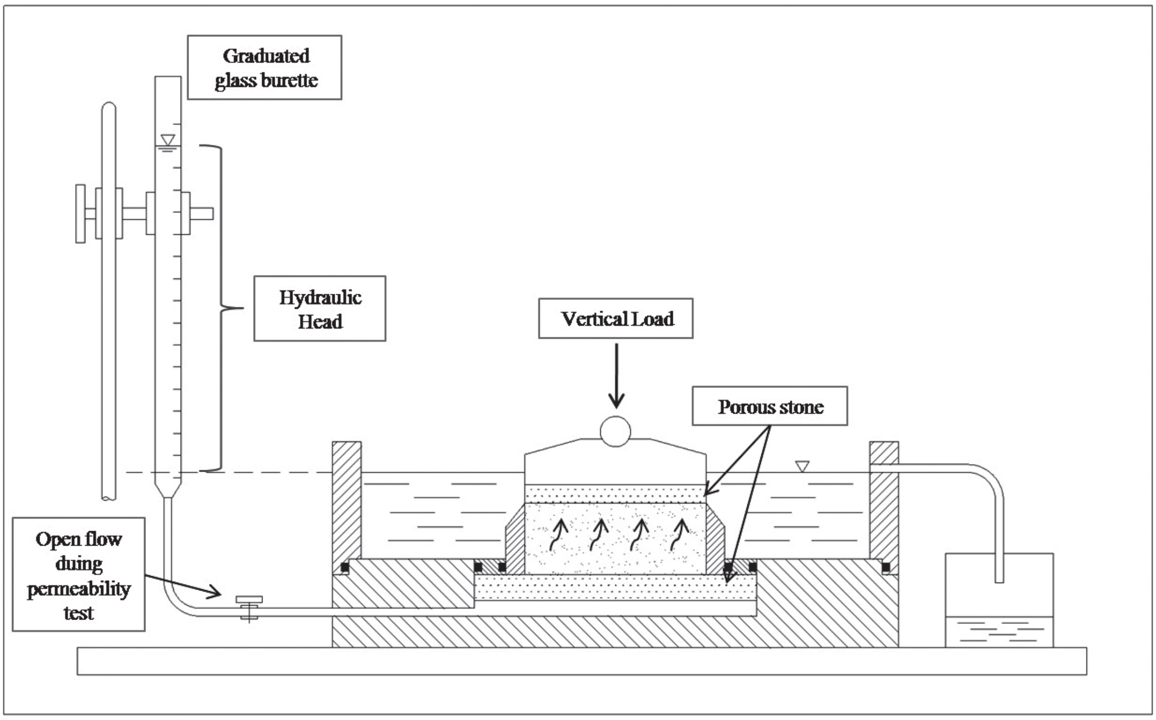

Fig. 2. Permeability — Test setup

does not coincide with that of the sample. As for TC soil the test conditions are summarized in Table 2a. Table 2b summarizes the test conditions as for 808I soil.

Table 2a

Summary of oedometer test conditions (TC soil)

Oedometer No. (Sample)	1	2	3	4	5
Dry unit weight γ_d (kN/m^3)	17.36	18.54	18.64	17.76	17.46
Total (initial) unit weight γ_{tot} (kN/m^3)	18.96	20.63	21.00	20.33	20.40
Final water content w_f (%)	15.5	14.7	14.1	15.6	18.7
Initial water content w_i (%)	9.2	11.0	12.9	14.4	16.8
Initial void ratio e_0	0.509	0.409	0.408	0.474	0.497
Initial saturation degree S_{ri} (%)	48	72	84	81	90

Table 2b

Summary of oedometer test conditions (808I soil)

Oedometer No. (Sample)	1	2	3	4	5
Dry unit weight γ_d (kN/m^3)	17.33	18.12	18.80	18.81	18.42
Total (initial) unit weight γ_{tot} (kN/m^3)	18.80	19.88	20.89	21.14	21.13
Final water content w_f (%)	19.6	18.2	16.8	15.3	15.4
Initial water content w_i (%)	8.5	9.7	11.1	12.4	14.7
Initial void ratio e_0	0.571	0.544	0.488	0.445	0.526
Initial saturation degree S_{ri} (%)	41	49	63	77	76

A graduated glass burette was connected to the lower porous stone. It was possible to appreciate a head variation of 0.5 mm corresponding to a volume variation as small as 48 mm^3. After checking the burette verticality, it was filled with distilled water and the hydraulic circuit was saturated. The specimens were subject to the conventional load sequence (25–50–100–200–400–800–1600–3200–6400–1600–400–100–25 kPa). Each loading step was kept for about 24 hours. At the end of each loading step, the burette was filled with distilled water in order to have an initial head of 50 cm. The head was evaluated with respect to the water level inside the oedometer cell. After that, the bottom drainage was opened and a variable head permeability test was performed. Permeability tests were not performed during the unloading stage. Head variation with time was manually recorded together with ambient temperature and variation of the specimen height, if any. The test was continued until the achievement of a stationary condition as shown in Fig. 3. In other words, we assume that after the first loading step and subsequent flow for the first k determination, the specimens are fully saturated. Of course we can determine only the initial and final water contents.

The saturated coefficient of hydraulic conductivity was computed by means of the following formula:

$$k = H\frac{a}{A}\frac{\ln(h1/h2)}{t2-t1} \qquad (1)$$

where:

- H = current height of the specimen;
- a and A = cross areas of the burette and specimen respectively;
- the term $\ln(h1/h2)/(t2-t1)$ represents the slope of the best — fit line of the experimental data (Fig. 3).

Figs. 4a and 4b show the variation of k with the effective vertical stress in a log-log scale, for the various initial densities. Fig. 4a refers to TC soil, while Fig. 4b shows the results for 808I soil. TC soil exhibits values of k (direct measurements) that are about one order of magnitude lower than those of 808I soil. More specifically, k of TC soil ranges in between 10^{-8} and 10^{-10} m/s, while the permeability of 808I soil ranges in between 10^{-7} and 10^{-9} m/s.

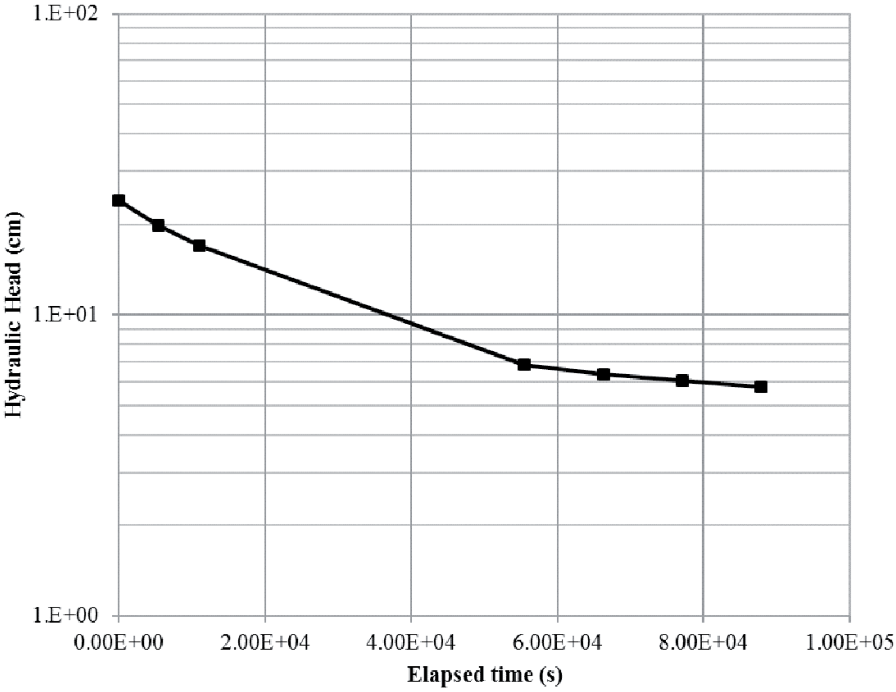

Fig. 3. Interpretation of permeability tests (808I soil — Giusti 2017 [13])

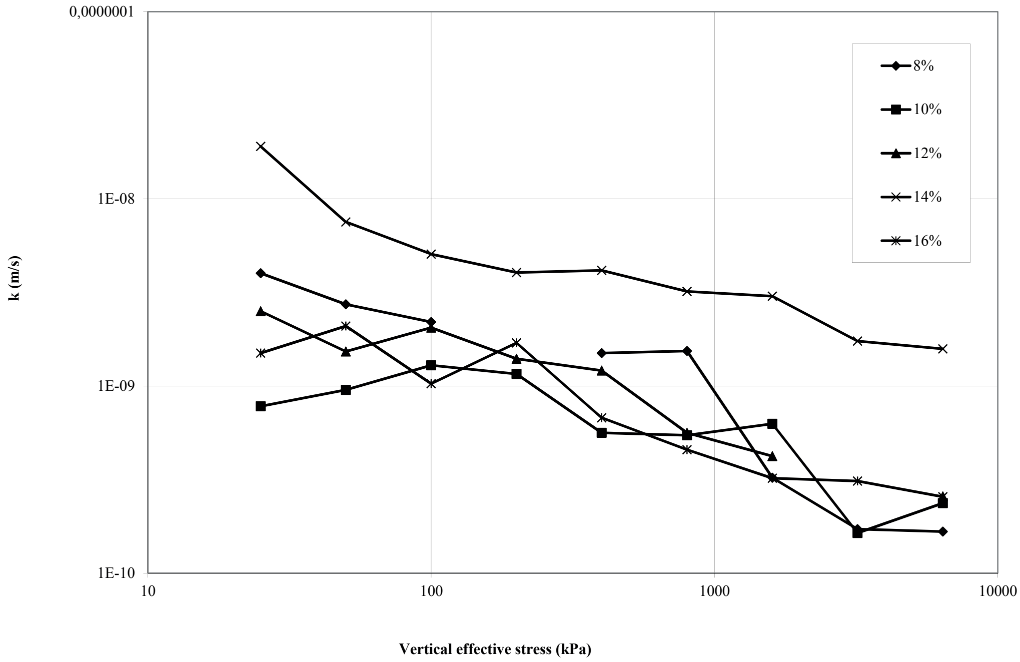

Fig. 4a. Variation of k with the effective vertical stress for the various initial water contents for TC soil (Carrai 2016) [11]

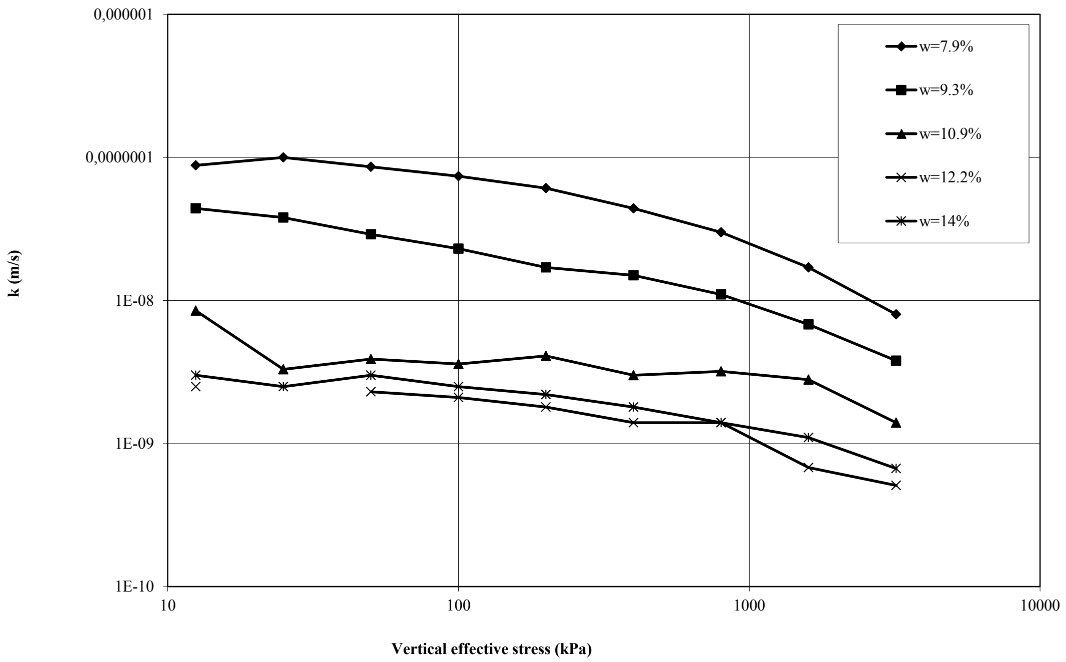

Fig. 4b. Variation of k with the effective vertical stress for the various initial water contents for 808I soil (Giusti 2017) [13]

The grain size effects on k can be evaluated by using the Hazen [14] or Prugh [17] approaches. These empirical equations are in principle applicable only to sandy soils and only consider the grain size characteristics of the soil (i.e. D_{50} and coefficient of uniformity or D_{10}). However, the differences in terms of k values between the two types of soils could be explained by considering the different clay percentage. Indeed, the clay fraction of TC soil (scalped) is twice that of 808I soil (scalped).

Permeability values, for the same type of soil, also depend on the initial compaction degree and on the applied effective stress. The influence of vertical effective stress on k is well known and stated in any textbook of soil mechanics (see as an example Lancellotta [15]). It is supposed that the increase of the vertical stress and consequent reduction of the void ratio lead to a reduction of k. For the tested soils, an almost linear relationship between log (k) and log (σ'_v) can be seen in both Figs. 4a and 4b (as expected).

The influence of the compaction degree on k, in the case of compacted soils, is not so well documented in literature. Experimental results shown in Figs. 4a and 4b suggest that, for a given soil, the specimens with a compaction degree very close to the optimum value exhibit the lowest permeability. At the same time the permeability decreases with an increase of the compaction degree.

More specifically, these observations are true for the whole range of applied stresses in the case of 808I soil (w_{opt} = 11.5 %). As for the TC soil (w_{opt} = 10.2 %) the above mentioned effects are evident mainly at low consolidation stresses. Apart the above observations, the effect of compaction degree (and consequently of initial water content) on k seems more complicated and needs additional considerations.

A comprehensive predictive model for k of compacted soils was proposed by Tatsuoka [21]. The Tastuoka's model is based on the experience of more than forty years in Japan and worldwide. More specifically, it is based on the following experimental observations:

- the saturated coefficient of hydraulic conductivity (k) for a given soil and a given range of the saturation degree linearly decreases with the dry density in a semi — log scale (Fig. 5a);
- the slope of the above relationship between log (k) and ρ_d is constant and equal to −5.02. The saturation degree during compaction does not affect such a constant (Fig. 5a);
- the effect of the saturation degree during compaction on k is very small or insignificant when Sr < 80 % (Fig. 5a);
- the data presented in Fig. 5a are those of SCM soil (Sieved Core Material of Miboro dam);
- data shown in Fig. 5b (Giusti 2017, [13]) confirms the Tatuoka's observations and refers to 808I soil. It is worth noting to remark that the Figure shows the saturated permeability as a function of the dry density. Different symbols are used for different initial degrees of saturation.

Based on the above observations, Tatsuoka [21] proposed the following equation to predict the permeability:

$$\mathrm{Log}(k) = \mathrm{Log} f_k(S_r) + 5.02 \cdot (1.872 - \rho_d / \rho_w) \quad (2)$$

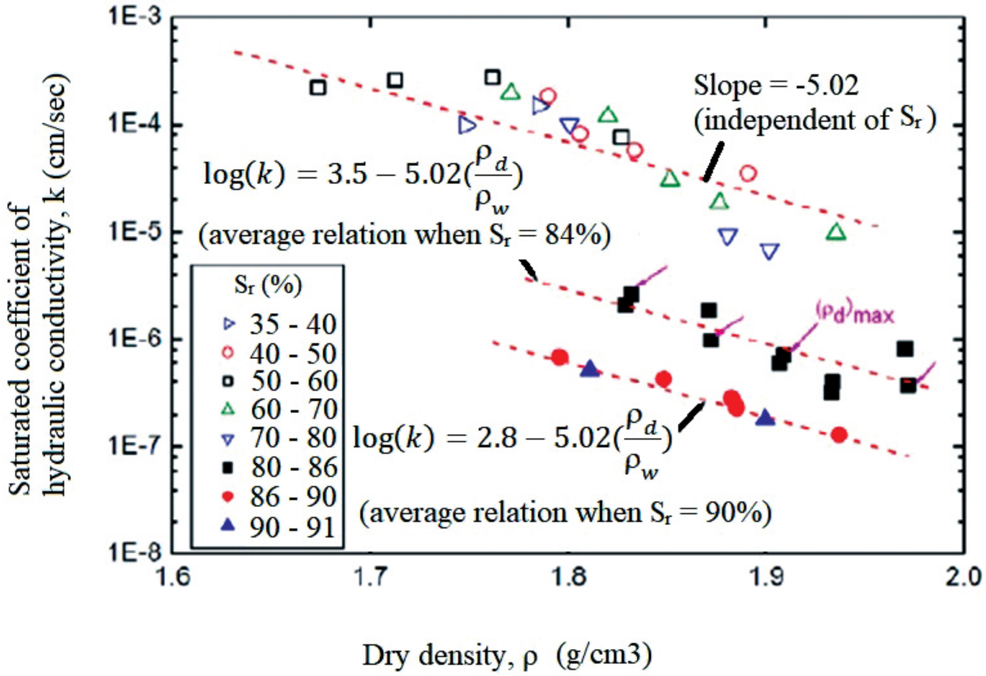

Fig. 5a. Dependence of *k* on the Saturation degree and Dry density (Tatsuoka 2015) [21]

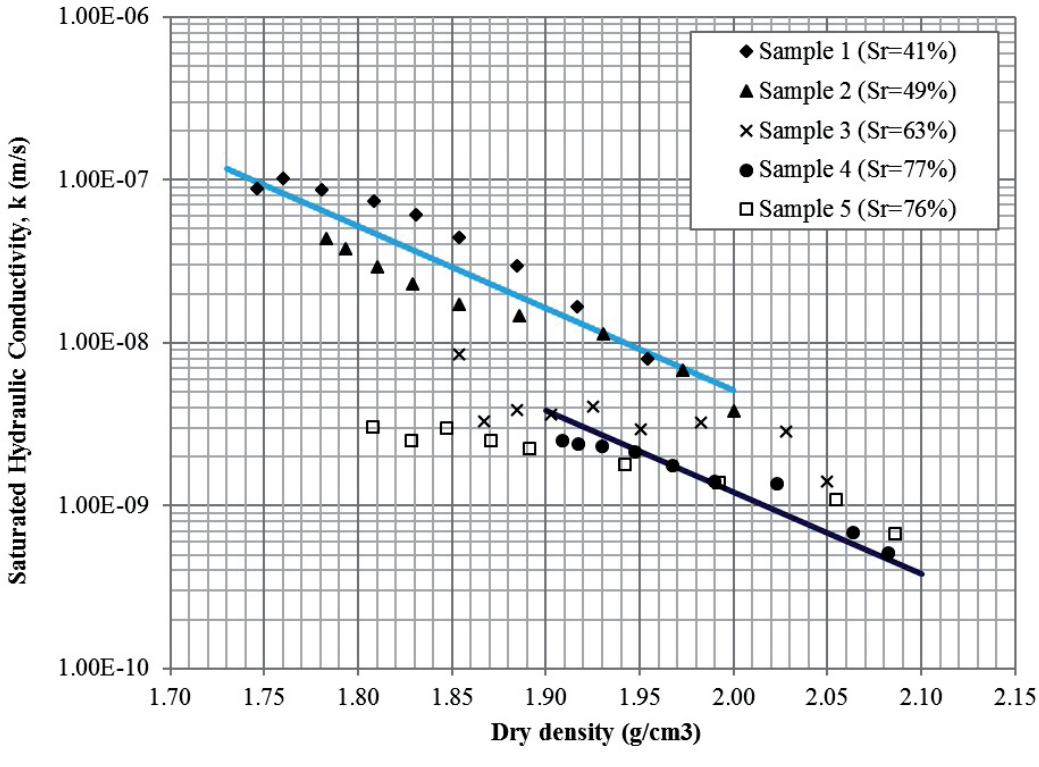

Fig. 5b. Dependence of *k* on the initial degree of saturation and dry density for 808I soil (Giusti 2017 [13] — data)

where: $\mathrm{Log} f_k(S_r)$ represents the dependence of k on the degree of saturation at the end of compaction; the term $5.02 \cdot (1.872 - \rho_d / \rho_w)$ represents the dependence of k on the dry density.

Tatsuoka [21], thanks to a huge amount of experimental data, proposed the following relationship for the term $\mathrm{Log} f_k(S_r)$ (eq. 2):

$$\mathrm{Log} f_k(S_r) = P + \mathrm{Log}[f_k(S_r)]_{SCM} \tag{3}$$

where: the particle size coefficient P can be obtained from data shown in Fig. 6 and the function $\mathrm{Log}[f_k(S_r)]_{SCM}$ is shown in Fig. 7.

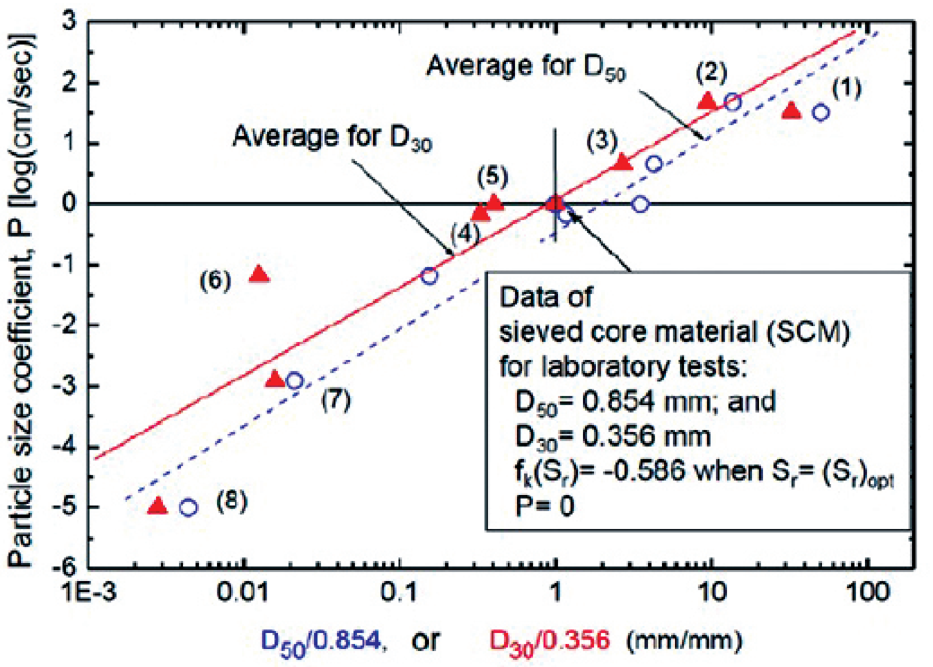

Fig. 6. Particle size coefficient (Tatsuoka 2015)

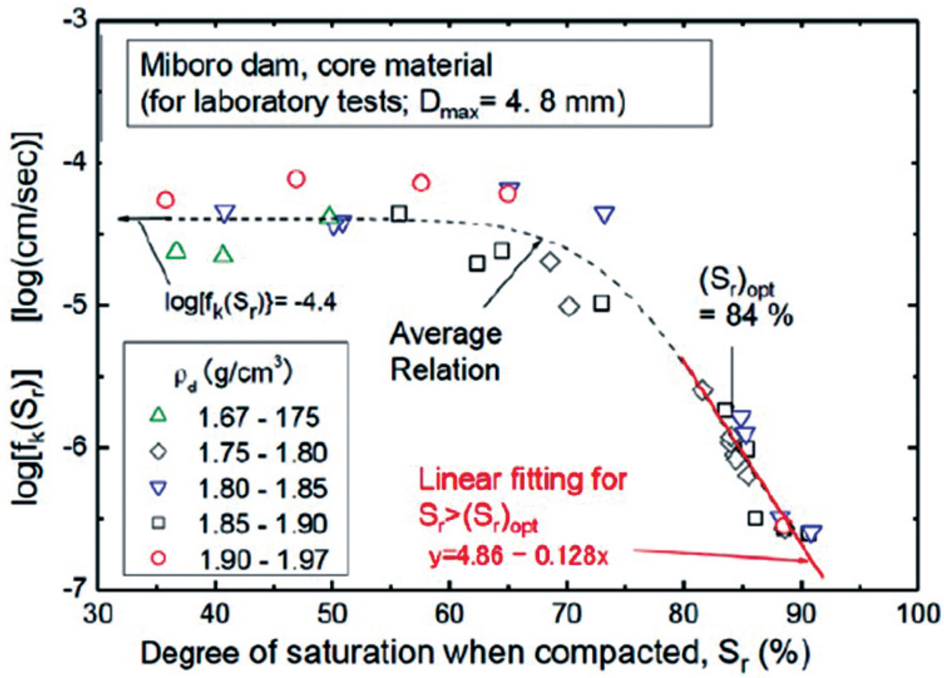

Fig. 7. Function representing the dependence of k on the saturation degree (Tatsuoka 2015, SCM Milboro Dam)

Fig. 8 compares the experimental results (808I soil) with the proposed model [13]. The Tatsuoka's predictive model fits very well the experimental results that were obtained for 808I soil during the present research. The variability, for each sample, in Fig. 8 is due to the effect of the vertical consolidation stress during oedometer tests. More specifically, the Fig. 8 shows the saturated permeability vs. the initial degree of saturation. The final degree of saturation is also known and equal to 100 %. On the other hand, the empirical assessment of the degree of saturation during the various consolidation steps is not possible. It was assumed a complete saturation after the first measurement of k at a vertical consolidation stress of 12.5 kPa.

The permeability that was inferred from C_v [22] and that obtained from direct measurements are compared in Fig. 9a and 9b for TC and 808I soils respectively. As for 808I soil, the two series show a certain agreement even though the scatter may be as much as one order of magnitude. As for the TC soil the direct measurements give values systematically higher than those obtained from C_v by means of the Taylor approach. Data shown in Fig. 9a and 9b make questionable the correctness of the indirect estimate of k from C_v and soil compressibility. It is worth noting that the compressibility for both soils is very low.

Triaxial Test Results and Effective Strength Parameters

The effect of suction on the effective strength parameters of soils is well documented in literature by experimental results. Alonso [3, 4] developed a predictive model for the effective strength parameters of partially saturated soils. On the other hand limited evidences are available in the case of compacted partially saturated soils (see as an example Varsei et al. [23]). In the present work, triaxial tests were performed on specimens compacted at different compaction degree and at the optimum water content. The compaction degree is defined as the ratio of the dry density to the maximum dry density. Different compaction degrees at the same water content were obtained by controlling the density of each layer and using different compaction energy.

Therefore the w–ρ_d data do not lie on the same compaction curve. After compaction, the samples were extracted from the Proctor mold and specimens were trimmed and transferred into the triaxial cell according to the usual procedures. Such operations caused a certain disturbance and the initial void ratio of the specimen does not coincide with that of the sample.

As far as the TC soil was concerned, three different types of triaxial tests were performed:

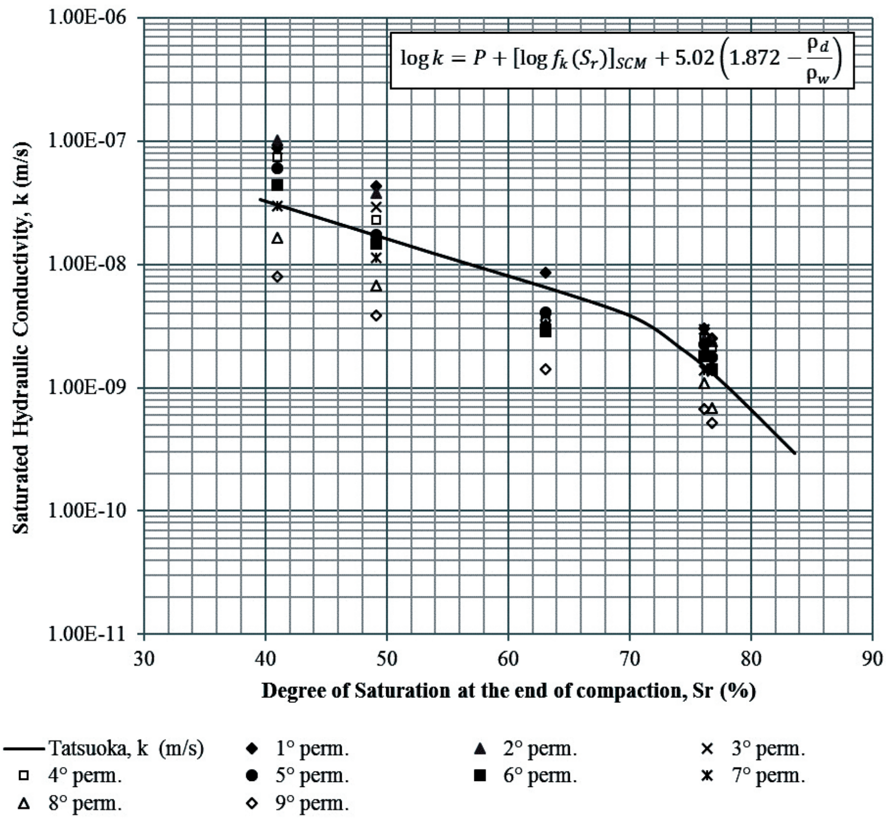

Fig. 8. Comparison between the experimental k values (808I soil) and the Tatsuoka's model (Giusti 2017)

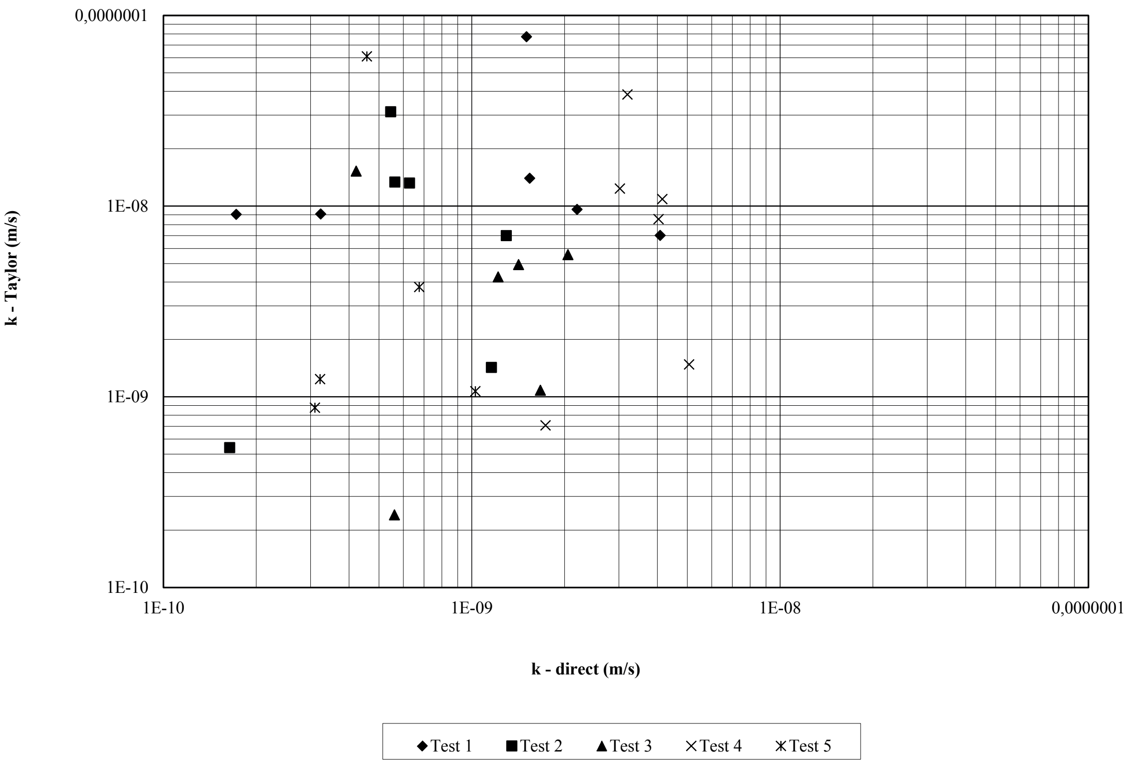

Fig. 9a. Comparison of *k* values from direct measurement and Taylor (1948) method (TC soil)

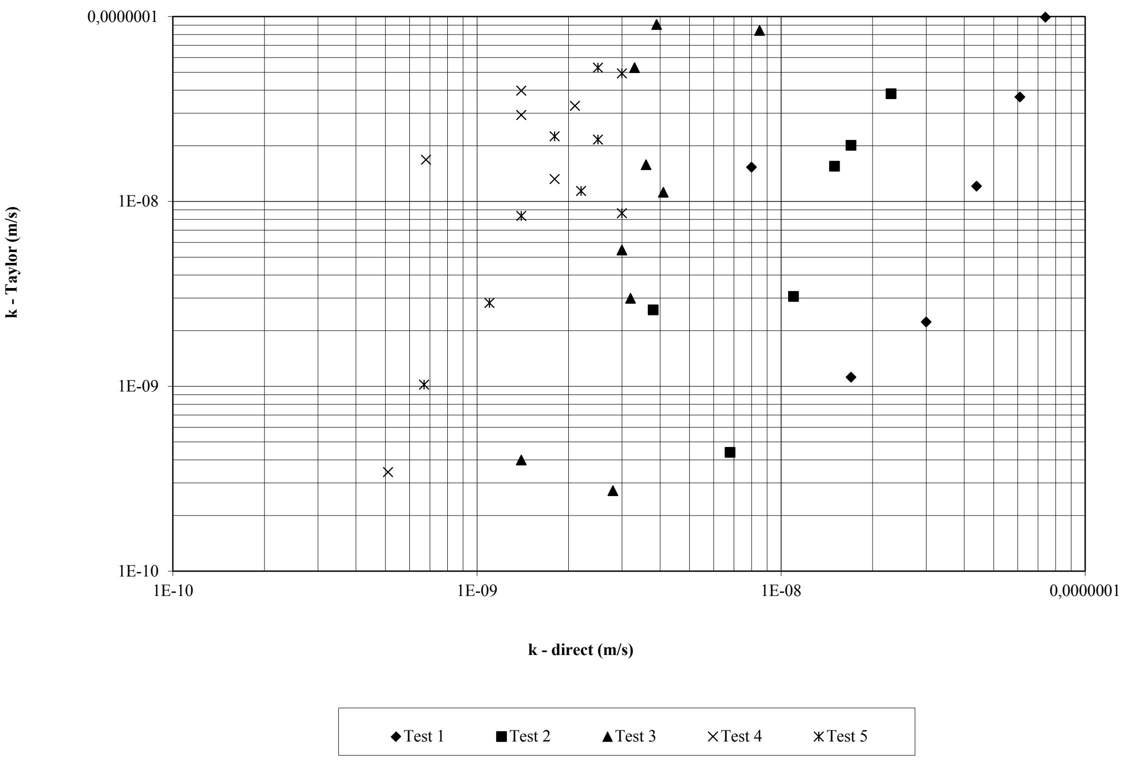

Fig. 9b. Comparison of *k* values from direct measurement and Taylor (1948) method (808I soil)

1. Compression loading triaxial tests on specimens compacted in the Proctor mould at different compaction degrees (about 80 and 90 %). The porous stones and filter paper were dry and the specimens had a water content of about 11–12 % (i.e the optimum water content). Specimens were isotropically consolidated and sheared under compression loading with free drainage (CID).

2. Compression loading triaxial tests on specimens reconstituted in the proctor mould at different compaction degrees (about 80 and 90 %). The specimens and testing apparatus were saturated with check of *B* parameter as usually and then sheared in compression loading with closed drainage (CIU).

3. Compression loading triaxial tests on specimens obtained from block samples. Two block samples were retrieved from the first metre of a levee that had been constructed by using TC soil. The porous stones and filter paper were dry and the specimens had a variable water content. Specimens were isotropically consolidated and sheared under compression loading with free drainage (CID). Other specimens, from block samples, were saturated, with check of the *B* parameter as usually, and then sheared in compression loading with closed drainage (CID).

Fig. 10 shows an example of undrained stress paths for the case of undisturbed (block samples) TC specimens. The whole test results are summarised in Tables 3 to 6 and Figs. 11 to 13. The upper part of Table 5 concerns the CID tests on undisturbed specimens (block samples), while the lower part summarizes the results of CIU tests. It is worth noting that the dry unit weight of the intact TC soil, at the Modified Proctor optimum, is equal to 18.54 kN/m^3.

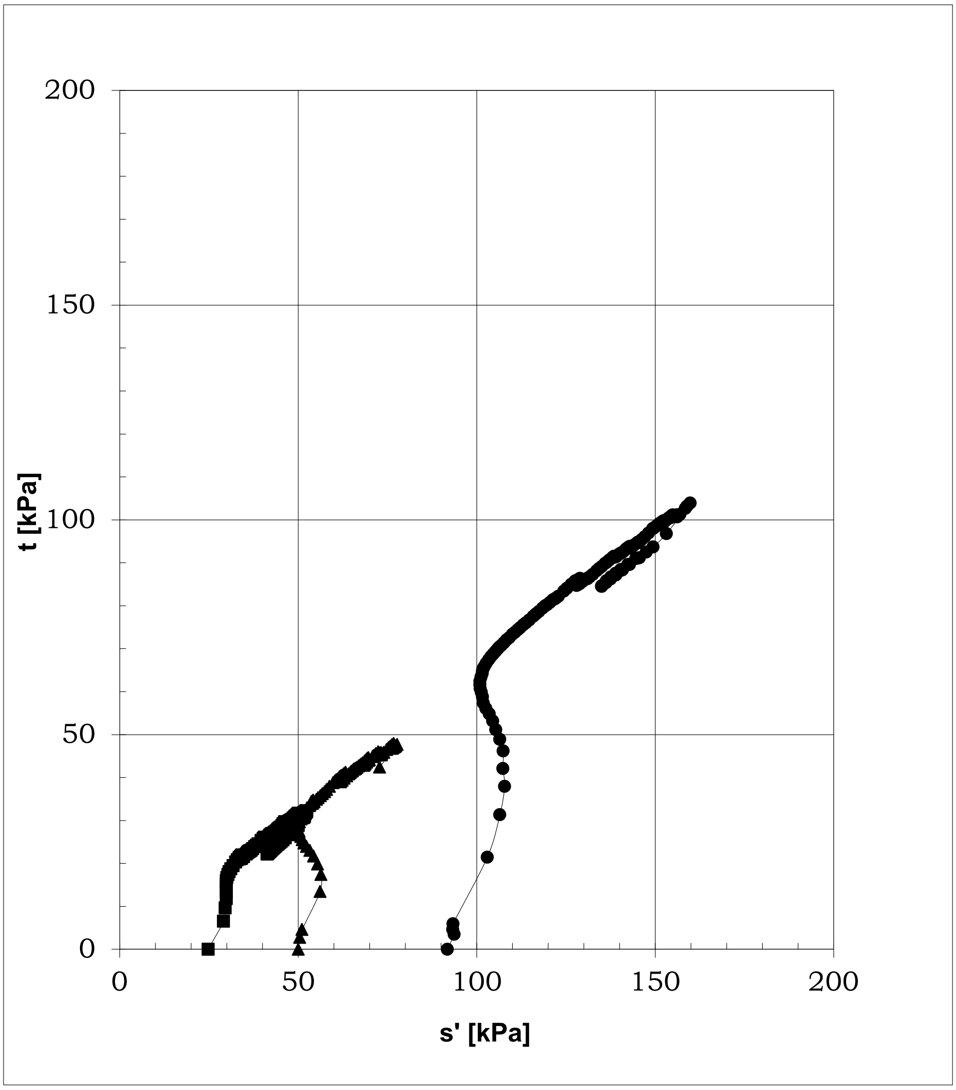

Fig. 10. Stress-paths — Compression Loading Triaxial tests on saturated undisturbed specimens (CIU)

Table 3

TC samples compacted at 80 and 90 % of the optimum dry density. Compression loading TX CID test results (partial saturation)

γ (kN/m^3)	Wi (%)	σ'_{1R} (kPa)	σ'_{3R} (kPa)	s' (kPa)	t (kPa)
17.54	11.04	43.96	0	21.98	21.98
16.97	11.47	115.36	40	77.68	37.68
17.51	11.49	267.01	80	173.505	93.505
17.13	11.46	59.11	0	29.555	29.555
17.04	11.47	135.81	40	87.905	47.905
17.23	10.94	294.58	80	187.29	107.29
19.46	11.46	86.82	0	43.41	43.41
19.33	11.46	242.2	40	141.1	101.1
19.12	11.34	350.3	80	215.15	135.15

Table 4

TC samples compacted at 80 and 90 % of the optimum dry density. Compression loading TX CIU test results (saturated condition)

γ (kN/m^3)	Wi (%)	σ'_{1R} (kPa)	σ'_{3R} (kPa)	s' (kPa)	t (kPa)
16.58	11.82	110.3	23.8	67.05	43.25
16.97	11.7	160.6	50.1	105.35	55.25
17.04	11.8	277.4	87.5	182.45	94.95
19.7	12.3	68.3	16.5	42.4	25.9
20	12.05	101.1	25.1	63.1	38
20	12.01	195.6	53.9	124.75	70.85

Table 5

TC block samples. Compression loading TX CIU and CID test results

γ (kN/m^3)	Wi (%)	σ'_{1R} (kPa)	σ'_{3R} (kPa)	s' (kPa)	t (kPa)
18.41	17.58	84.86	20.36	52.61	32.25
19.09	19.62	124.69	28.89	76.79	47.9
19.10	16.39	271.92	64.12	168.02	103.9
18.49	18.49	138.53	35.13	86.83	51.7
19.23	17.65	221.94	51.44	136.69	85.25
19.94	11.8	377.94	107.44	242.69	135.25
18.21	20.68	61.50	0	30.75	30.75
18.41	21.13	150.98	40	95.49	55.49
18.28	23.62	302.51	80	191.25	111.25
18.27	17.66	48.10	0	24.05	24.05
19.70	17.80	135.03	40	87.51	47.51
19.90	16.62	80.40	0	40.20	40.20
18.80	16.65	75.50	0	37.75	37.75
18.55	15.87	144.08	40	92.04	52.04
19.49	14.89	150.60	40	95.30	55.30

Table 6

TC Mohr-Coulomb strength parameters

Soil type	Test Conditions	c' (kPa)	φ' (°)
TC	Compacted 80 %, Partially saturated (CID)	9.6	29.9
TC	Compacted 90 %, Partially saturated (CID)	25.7	32.5
TC	Compacted 80 % and 90 %, fully saturated (CIU)	8.6	29.0
TC	Undisturbed specimen (block sample), 80–90 %, (CIU and CID)	12.6	30.9
808I	Compacted 90 %, fully saturated (CIU)	10.4	42.2

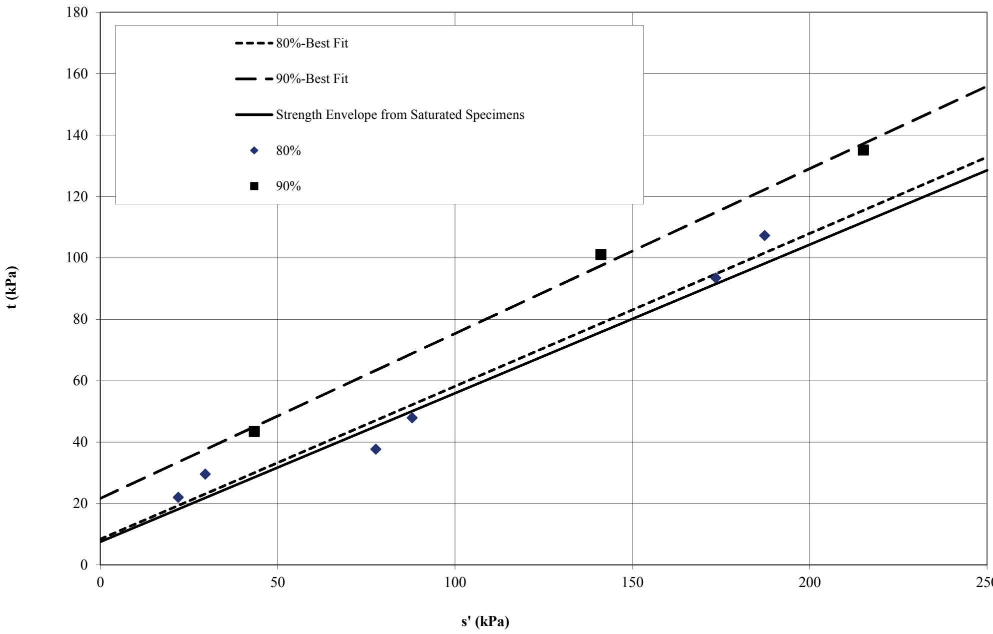

Fig. 11. Compression Loading Triaxial tests on partially saturated compacted specimens (CID)

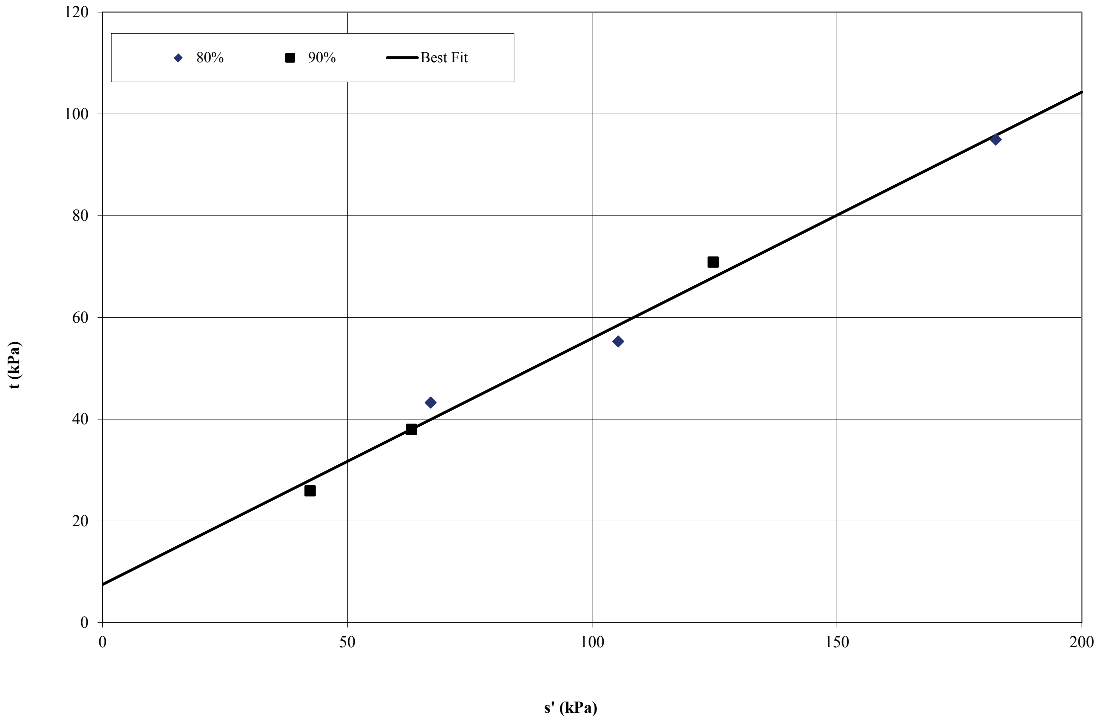

Fig. 12. Compression Loading Triaxial tests on fully saturated compacted specimens (CIU)

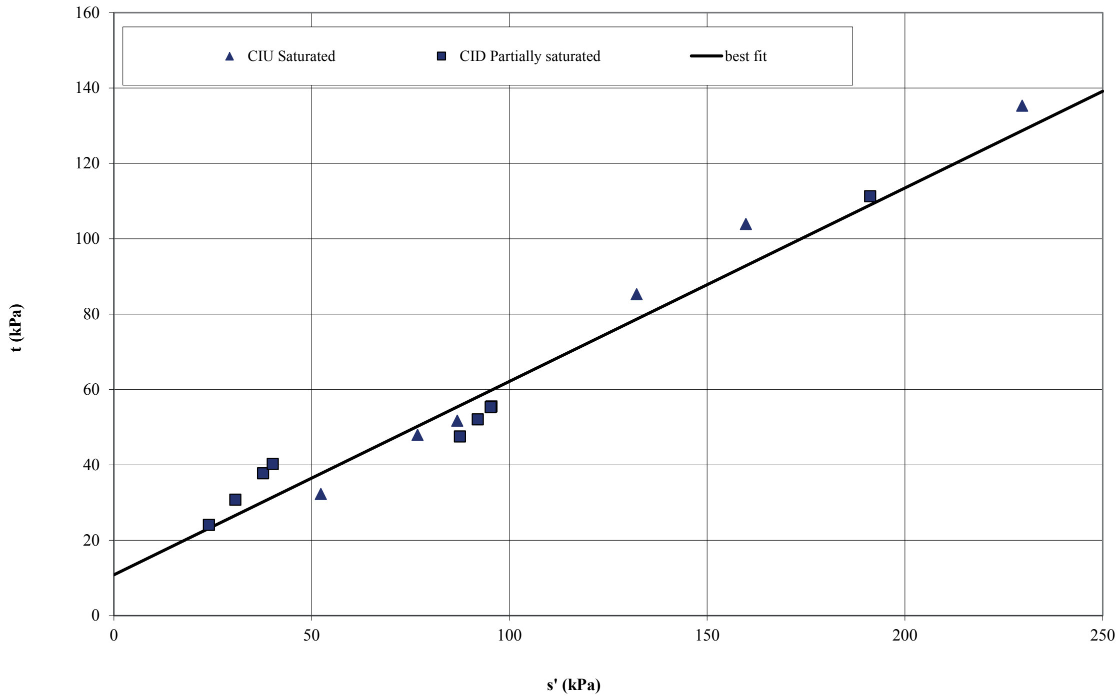

Fig. 13. Compression Loading Triaxial tests on undisturbed specimens —
Block Sample (CIU and CID)

It is possible to comment the results in the following way (all comments refer to peak condition):

1. Compacted specimens with a compaction degree of 90 % and a water content equal to about the optimum water content exhibit a cohesion of up to 26 kPa and a friction angle of 32.5°.
2. Compacted specimens with a compaction degree of 80 % and a water content equal to about the optimum water content exhibit a cohesion of up to 10 kPa and a friction angle of 30°.
3. Compacted and saturated specimens with a compaction degree of 80 and 90 % exhibit the same strength envelope. The obtained strength parameters are the same of compacted specimens with a compaction degree of 80 % but tested under the condition of partial saturation.
4. As for the block samples, the strength parameters apparently exhibit some differences with respect to those of the compacted specimens, but in practice the two strength envelopes coincide. It is worth noting that block samples have a coarser fraction that has been eliminated in the case of compacted specimens and moreover also the optimum density is different.
5. As for the saturated specimens (compacted or from block samples) it would be expected a curve envelope with zero cohesion. This is not the case. Different explanations are possible: a) strength — envelope curvature appears at very low confining stresses (unfortunately with the available equipment, it is not possible to maintain very low confining stresses); b) trimming produces a very high disturbance which delete the benefit of compaction; c) compaction — induced co — action causes a permanent cohesion which cannot be deleted by the full specimen saturation as well as by disturbance during transferring and specimen trimming.

In conclusion, compacted soils (at least for a compaction degree between 80 and 90 %) exhibit certain cohesion. The highest values of the cohesion are observed in the case of partially saturated specimens (optimum water content) and compacted at 90 % of the optimum. As for the friction angle, in practice it seems not too much affected by the test conditions (water content, compaction degree).

Fig. 14 shows the strength envelope in the case of 808I soil. The obtained results seem in line with what has been observed in the case of the TC soil. The friction angle of 808I soil is much higher than that obtained for the TC soil. The 808I soil is indeed much sandy and silty than TC soil.

Conclusions

This experimental investigation has shown that both the saturated coefficient of hydraulic permeability and the apparent cohesion depend on the compaction degree and water content (or saturation degree) during compaction. Therefore, it could be possible, in principle, to infer these parameters (for a given earthwork) from the knowledge of the compaction degree and water content. It is worth noticing that the dependence of the apparent cohesion on the compaction degree is more pronounced in the case of partial saturation (suction effects). Therefore, when assessing the safety factor of any earthwork it may be of fundamental importance to evaluate (control) the compaction degree and in situ water content.

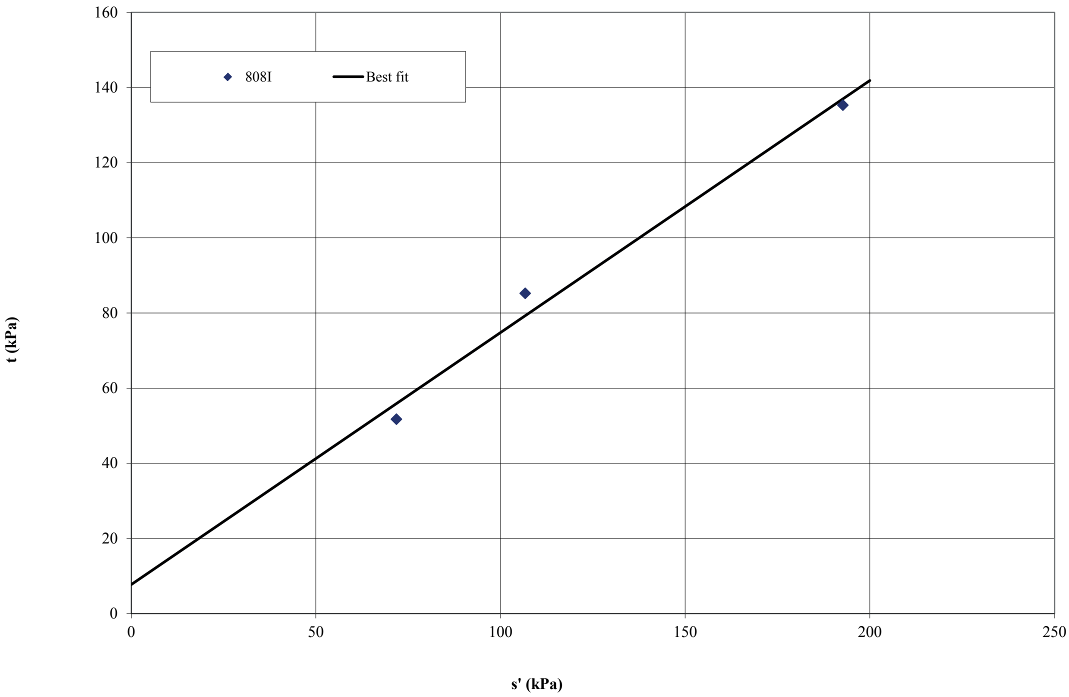

Fig. 14. Compression Loading Triaxial tests on fully saturated compacted specimens of 808I soil (CIU)

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